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DESIGN AND DEVELOPMENT OF PILL-BOX WINDOW AND A WAVEGUIDE COUPLER FOR TRAVELING-WAVE TUBES

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***Abstract*— The present work aims is to design, fabricate and cold test measurement of a waveguide based RF window and coupler for traveling-wave tubes. The initial design was based on cascaded matrix method for the pill box window and simple parametric approach for the waveguide coupler. Validation of the analytical design for window and coupler are carried out by numerical simulation using a 3D numerical simulation code CST-Microwave studio. Realization of piece parts, assembly and cold test measurement of the window and coupler for VSWR characteristic also carried out and the results are compared.**

I. INTRODUCTION

A microwave window for high power tube applications may be defined as a waveguide structure, which protects the tube's vacuum envelope from the outside atmosphere and functions as a vacuum-vacuum or vacuum-pressure barrier that is essentially transparent to the flow of microwave energy [1]. RF windows for microwave tubes, in general, can be classified on the basis of the transmission system used, shape, and size and according to their functions as coaxial or waveguide. The waveguide coupler is used to match the impedance of the RF window to the RF interaction structure of the TWT [2].

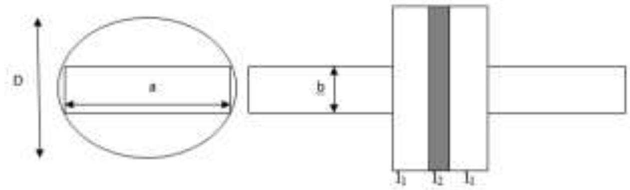
In this present work, the design of waveguide based RF window and coupler is carried out at mm-wave frequency. The waveguide window is used mainly for high power handling capability. Since the dielectric element comes in the part of propagating microwave power, it causes the reflection and absorption of this power. A constant deposition of microwave energy in the ceramic due to dielectric loss results in the rise of the window ceramic temperature and may produce thermal runaway due to temperature dependent loss properties of the window ceramic. The coupler designed in this present work is tapered transitions which match the impedance of the RF window to the interaction structure of the TWT at mm-wave frequency.

II. DESIGN OF RF WINDOW AND COUPLER

A. Design of RF window

The ideal window design aims to provide high percentage power transmission and low reflections over the required frequency range, low electrical and mechanical stress on the metal-to-dielectric seal and minimum field strength around broad-handling elements to avoid high-power breakdown. The ideal window dielectric has the following properties: low dielectric loss to reduce heat generated, high thermal conductivity to facilitate the removal of heat that is generated by loss, bombardment, Low dielectric constant to keep the shunt susceptance introduced by the window to a minimum and so aid broad-banding and high mechanical strength both to facilitate sealing and to keep the amount of dielectric introduced to a minimum.

The pill box structure is a complex window structure from microwave analysis and design point of view because of multiple discontinuities spaced quite closely. A pillbox window consists of a thin ceramic disc mounted at the centre of a short section of a circular waveguide, which in turn is terminated at is input and output with standard rectangular waveguide as shown in Fig.1.



(a) **(b)**

Fig.1 Schematic of pill box window (a) cross sectional view and (b) longitudinal view

The RF design of pill box window is carried out using cased matrix approach reported in [1]. The discontinuity susceptance between the rectangular waveguide and circular waveguide is given by,

$$B_T = \frac{b}{\lambda_{gr}}\left\{2ln\left(\frac{D^2-b^2}{4bD}\right)+\left(\frac{b}{D}+\frac{D}{b}\right)ln\left(\frac{D+b}{D-b}\right)+2\sum_{1}^{\infty}\frac{sin^2 n\phi}{n^3\phi^2}\delta_{2n}\right\} \quad (1)$$

Where 'D' is the diameter of circular waveguide, 'a', 'b' are the wide and narrow dimensions of rectangular waveguide,

'β' propagation constant, 'λ_{gr}' guide wavelength of rectangular waveguide, 'λ_{gc}' guide wavelength of circular waveguide, 't' thickness of dielectric, 'ω' angular frequency, 'c' velocity of light, 'ε_r' dielectric constant, 'λ' free space wavelength.

$$\delta_{2n} = \frac{1}{\sqrt{1-\left(\frac{\beta D}{2\pi n}\right)^2}} - 1$$

$$\beta = \frac{2\pi}{\lambda_{gr}},\ \phi = \frac{\pi b}{D}$$

According to transmission line theory, the pillbox window has three discontinuities: rectangular to circular waveguide, dielectric piece and circular wave-guide to rectangular wave guide. These discontinuities can be equaled to a discontinuity of transmission line. So the simplified equivalent circuit of pillbox window is obtained as shown in Fig 2. Z_1 is characteristic impedance of circular waveguide.Z_2 is characteristic impedance of the rectangular waveguide. Bd is normalized susceptance of the dielectric piece. BT is normalized susceptance of the discontinuity between rectangular and circular waveguide

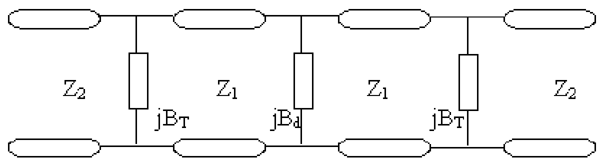


Fig.2 Simplified equivalent circuit for pillbox window

From equivalent network theory, two-port matrix expression of the equivalent circuit is [2]

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \sqrt{k} & 0 \\ jBT\sqrt{k} & 1/\sqrt{k} \end{bmatrix} \begin{bmatrix} \cos\gamma l & j\sin\gamma l \\ j\sin\gamma l & \cos\gamma l \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jBd & 1 \end{bmatrix} \times \begin{bmatrix} \cos\gamma l & j\sin\gamma l \\ j\sin\gamma l & \cos\gamma l \end{bmatrix} \begin{bmatrix} 1/\sqrt{k} & 0 \\ jBT\sqrt{k} & \sqrt{k} \end{bmatrix} \tag{2}$$

Where $k = Z_1/Z_2$ impedance ratio

$\gamma = \frac{2\pi}{\lambda_{gc}}$ Propagating constant in circular wave guide

λ_{gc} = wave-guide wavelength of circular wave-guide

The susceptance produced by dielectric piece is given by [3]

$$Bd = t(\varepsilon_d - 1)\left(\frac{\omega}{c}\right)\left(\frac{\lambda_{gc}}{\lambda}\right)$$

Where t = thickness of dielectric piece, ε_d = dielectric constant of the dielectric piece,ω = Angular frequency, c = light velocity,λ = free space wavelength.

Assuming the input power of the window is P_1 and the power transmitting the window is P_2, we have

$$\left|\frac{P2}{P1}\right| = \frac{1}{1+\frac{1}{4}(B-C)^2}$$

The reflection coefficient of the window is

$$|\Gamma| = \left[\left|1-\left(\frac{P2}{P1}\right)\right|\right]^{\frac{1}{2}} \tag{3}$$

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{4}$$

B. Design of tapered line for folded waveguide structure

When the rectangular waveguide is folded along longitudinal, a slow wave circuit is formed for electron beam traveling on axis. Folded waveguide as shown in Fig.3 is suitable for broad high power mm-wave TWTs.

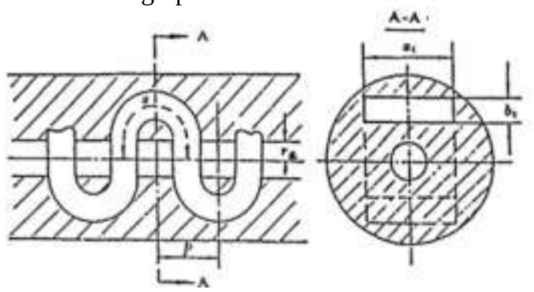


Fig. 3 Scematic of folded waveguide structure

In order to match the impedance of the folded-waveguide structure to RF window, the impedance transformer must be designed. In this present work a linear double taper was designed using the approach reported in [3].

Assuming the width and height of rectangular waveguide are a_0 and b_0 for input and output energy coupler, the length of linear double taper is L. when input and output wave guide connect with folded waveguide, reflection coefficient of the taper is

$$|\Gamma| = \frac{\lambda}{L}\left[\frac{K_0^{\,2}+K_1^{\,2}}{64\pi^2} - \frac{K_0K_1}{32\pi^2}\cos(4\pi d)\right]^{\frac{1}{2}} \tag{5}$$

Where

$$K_0 = \frac{(b_1-b_0)/b_0 - (a_1-a_0)/[a_0(1-(\lambda/2a_0)^2)]}{[1-(\lambda/2a_0)^2]^{1/2}}$$

$$K_1 = \frac{(b_1-b_0)/b_1 - (a_1-a_0)/[a_1(1-(\lambda/2a_1)^2)]}{[1-(\lambda/2a_1)^2]^{1/2}}$$

$$d = \frac{L}{2(a_1-a_0)}\left[\frac{2a_1}{\lambda_{g1}} - \frac{2a_0}{\lambda_{g0}} + \tan^{-1}\frac{2a_0}{\lambda_{g0}} - \tan^{-1}\frac{2a_1}{\lambda_{g1}}\right]$$

$$\lambda_{g0} = \lambda/\sqrt{1-(\lambda/2a_0)^2}$$
$$\lambda_{g1} = \lambda/\sqrt{1-(\lambda/2a_1)^2}$$

For linear double taper, the longer length L of taper, the smaller reflection coefficient Γ. However hope the length L of taper as short as possible under permissive matching condition. When the taper is designed, we can calculate the reflection coefficient in various L, and then shortest length L_{min} can be easy determined in center frequency, while the matching characters are obtained in operating band width.

C. RF analysis using CST-microwave studio

CST-Microwave studio is an interactive FEM based commercially available 3D electromagnetic simulation software package used for optimization as well as for validation of the computed results from analytical mode [4]. The window is considered as a two port device. The 3D model as well the electric field arrow plots are shown in Fig. 4. The excited waveguide port is considered as an input port- and the other port is considered as an output port. The VSWR is computed at both the ports. Similarly the 3D model as well the electric field arrow plots for the linear double taper is shown in Fig. 5.

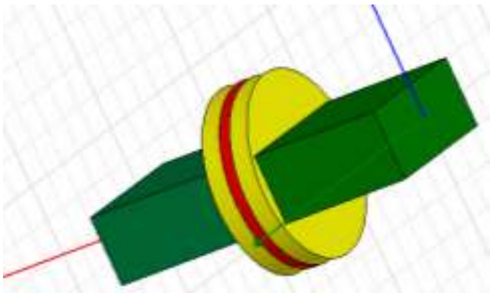


Fig.4 (a) 3D model of pillbox window

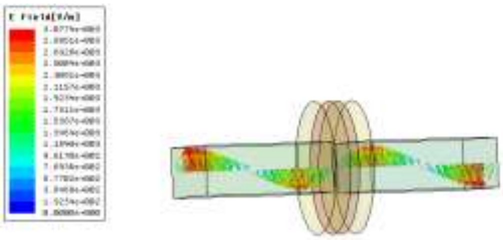


Fig.4 (b) E field vector plot for pillbox window

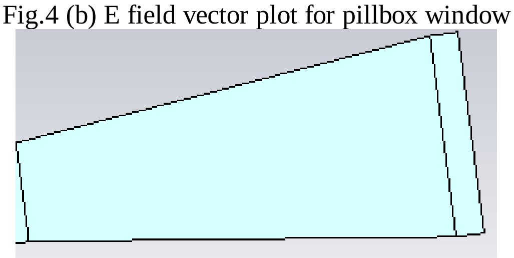


Fig.5 (a) 3D model of a coupler waveguide

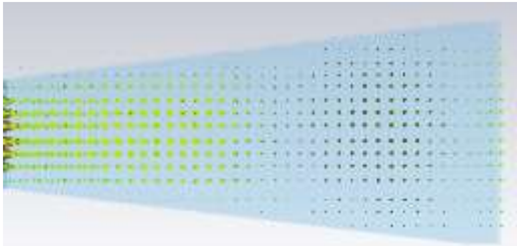


Fig.5 (b) E field vector plot for a coupler waveguide

D. Cold test measurement

The piece parts for the window were fabricated and assembled for cold test measurement. The cold test measurement has been carried out by using a HP N5227A network analyzer for VSWR characteristics. The comparison of VSWR characteristics from the analytical results against numerical simulation and cold test measurements of a pillbox window and couplers are shown in Fig.6 and Fig.7 respectively.

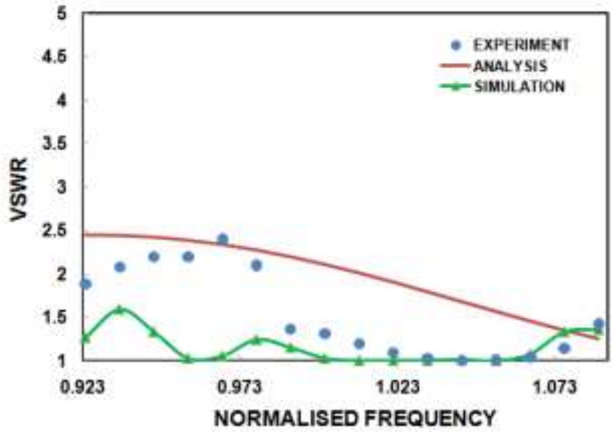


Fig. 6 Comparison of VSWR characteristic from the analytical results and cold test measurements of pillbox window

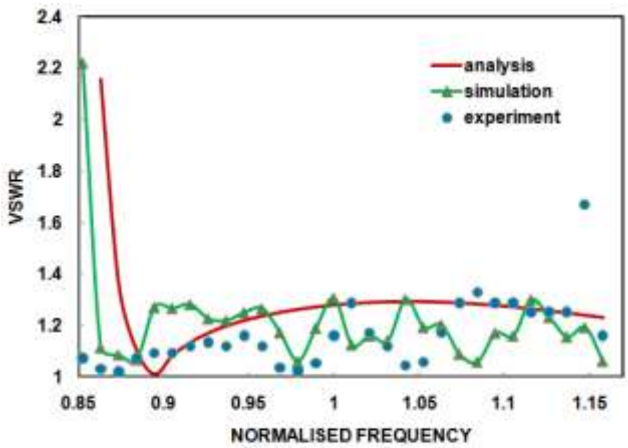


Fig. 7 Comparison of VSWR characteristics from the analytical results against numerical simulation and cold test measurements of coupler

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